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Verification of VMTF Relief Sizing for LARP High-Field Magnet Testing

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Abstract:

The installed relief devices are verified to be sufficient to protect the Vertical Magnet Test Facility (VMTF) during LARP high-field magnet testing.

Introduction

The purpose of this document is to verify that the in-service relief system at the Vertical Magnet Test Facility (VMTF) is adequate for testing LHC Accelerator Research Program (LARP) high-field magnets.

System Parameters

Relief systems for MTF test stands are sized to protect the cryogenic system in the event of loss of insulating vacuum to helium (CGA S-1.3 para. 5.2.2), fire (CGA S-1.3 para. 5.3.3), loss of insulating vacuum to air, quenching, and simultaneous quenching and loss of insulating vacuum to air. This final event generally requires the greatest venting capability. The installed relief system at VMTF consists of two Series 81, G (0.503 in^2) orifice Anderson-Greenwood valves with setpoints of 50 psig and 65 psig and one 1-1/2" Fike HOV-BT rupture disk with a 100 psig setpoint.

This relief system was originally sized for testing the HGQ series magnets with a maximum heat input to the helium of 112 kW. Loss of insulating vacuum to atmosphere accounts for 68 kW. The remaining 44 kW results from an ensuing full-energy deposition quench with the assumption of He I pool boiling [1].

The maximum length, maximum stored energy per unit length, and coil cross-sectional area for the two LARP high-field magnet series to be tested in VMTF are shown in Table 1 [2]. A 90 mm magnet bore is assumed.

Table 1 Characteristics of the two LARP high-field magnet series.

Magnet Series	Maximum Length [m]	Maximum Stored Energy [kJ/m]	Coil Cross-Section [cm^2]
LM	4	145	11.17
TQC	4	224	29.33

Analysis

The coil temperature rise following a full-energy deposition quench was calculated for each LARP magnet series. These calculations assumed the energy is uniformly deposited in the coils. The coils are also assumed to be a 1:1 ratio of Nb_3Sn and OFHC copper. Specific heat data for Nb_3Sn and OFHC copper were gathered from [3] and [4], respectively. The calculated maximum coil temperature rises for the LM and TQC magnets are 130 K and 100 K, respectively.

These values were then used to estimate the initial heat flux in He I pool boiling based on the temperature difference between the coils and the liquid helium [5]. With a 90 mm magnet bore, the heat transfer surface area is 1.13 m^2 = 11,300 cm^2. The initial quench heat deposition rate of the LM series magnets is expected to be nearly twice that of the HGQ series magnets. The TQC initial quench heat deposition rate is 28% greater than that of the HGQ magnets. Results are summarized in Table 2.

Table 2 Calculated maximum coil temperature rise, initial heat flux, and initial heat transfer rate following a full-energy deposition quench.

Magnet series	Calculated ΔT_{max} [K]	Initial heat flux [W/cm^2]	Initial heat transfer rate [kW]
LM	130	7.1	80.2
TQC	100	5.0	56.5
HGQ			44

It is important to note that these calculations assume He I pool boiling. The VMTF helium vessel has a maximum allowable working pressure (MAWP) of 98 psia. As the vessel pressure rises above the critical pressure of 32 psia, the mode of heat transfer changes from pool boiling to free convection.

For free convection calculations, the coil temperature when the pressure goes above the critical pressure must be estimated. The VMTF Engineering Note includes a calculation of the pressure and temperature inside a closed test dewar (i.e., no power lead or other vent flows) with a constant 112 kW of heat added. Approximately 2 s are required to reach the critical pressure. At 112 kW, this is a total heat input of 224 kJ. The coil temperatures can then be calculated after this amount of energy has been transferred to the helium. The calculated temperatures are 104 K for the LM magnet and 91 K for the TQC magnet.

With these coil temperatures and the free convection heat transfer correlations [6] included in the Appendix, the heat transfer rate to the supercritical helium can be calculated. Table 3 compares the tabulated He I pool boiling heat flux [5] and the calculated free convection heat flux as a function of temperature difference between the coils and the helium. The free convection heat flux is approximately one order of magnitude smaller.

Table 3 Comparison of He I pool boiling heat flux and free convection heat flux.

ΔT [K]	He I pool boiling q'' [W/cm^2]	Free convection q'' [W/cm^2]
10	0.30	0.051
20	0.63	0.093
50	2.2	0.21
100	5.0	0.38
150	7.9	0.54
200	12.6	0.69

With a $\Delta T \sim 100$ K based on the calculated coil temperatures of 104 K (LM series) and 91 K (TQC series), the free convection heat flux is 0.38 W/cm^2. The total heat transfer rate to the supercritical helium following a full-energy deposition quench is 4.3 kW once the critical pressure has been surpassed. For loss of insulating vacuum followed by a full-energy deposition quench, the heat transfer rate to the helium is therefore 68 kW + 4.3 kW = 72.3 kW. The relief system was sized for 112 kW and is more than adequate with a margin of 39.7 kW.

Another situation that has been encountered is a runaway power supply. Each of the six 5 kA power supplies that comprise Cryogenic Power Supply 3 (CPS-3) has a maximum power output of 150 kW (5000 A at 30 Vdc). The six power supplies working together can thus supply up to 900 kW, while the relief system has a margin of 39.7 kW. A heat flux of 39,700 W/11,300 cm^2 = 3.5 W/cm^2 is required in order for this margin heat input to be transferred to the helium. Given the low heat transfer rate to supercritical helium, a temperature difference of many hundreds of degrees between the coil and the helium is required to transfer this much heat. Most of the input power from the power supplies will therefore remain in the magnet. The expected failure mode is then melted solder at a splice, not overpressurization of the helium vessel.

Conclusions

Calculations indicate that the initial quench heat deposition rates for the LARP magnets will be up to twice that of the HGQ magnets. This means that during testing of a LARP high-field magnet, the initial pressure rise following a quench is expected to be greater and faster than that seen during HGQ testing. Once the vessel pressure exceeds the critical pressure, however, the heat transfer rate is reduced by an order of magnitude. The relief system is sized based on the MAWP of the helium vessel, which is well above the critical pressure, and so the installed relief system sized assuming pool boiling is more than adequate to protect the helium vessel under all emergency conditions.

The relatively poor supercritical heat transfer rate also means that a runaway power supply is expected to cause a magnet failure long before the helium vessel overpressurizes.

References

1. T. Peterson, "VMTF Cryogenic System Safety Report," 1996.
2. S. Feher, private communication, May 2006.
3. P. Bauer, "Preliminary Quench Protection Calculations for the 1st Fermilab Common Coil React and Wind," Technical Division Note TD-99-054, 1999.
4. National Institute of Standards and Technology (NIST), Cryogenic Technologies Group Material Properties web page (http://cryogenics.nist.gov/NewFiles/material_properties.html)
5. S. Van Sciver, *Helium Cryogenics*, Fig. 6.15, p. 223.
6. W. Rohsenow et al., *Handbook of Heat Transfer*, 3rd ed., pp. 4.34-4.35.

Appendix

Free convection heat transfer correlations are appended.

FREE CONVECTION IN SUPERCRITICAL HELIUM

Dimensionless numbers

$Nus = \frac{q \cdot r}{perim \cdot H \cdot (T_{coil} - T_{inf}) \cdot k}$ Nusselt number

$Nus = \left[\left(\frac{Ra}{16}\right)^m + (c \cdot \overline{C}_l \cdot Ra^{(1/4)})^m\right]^{\left[\frac{1}{m}\right]}$ Nusselt number

$\overline{C}_l = \frac{0.671}{\left[1 + \left(\frac{0.492}{Pr}\right)^{\left(\frac{9}{16}\right)}\right]^{(4/9)}}$ coefficient

$c = 1.2$ coefficient

$m = -1.03$ exponent

$Ra = \frac{g \cdot \beta \cdot (T_{coil} - T_{inf}) \cdot r^3}{\nu \cdot \alpha} \cdot \frac{r}{H}$ Rayleigh number

$Pr = \frac{\mu \cdot cp}{k}$ Prandtl number

Dewar conditions

$P = 98 \cdot \left[6894.758 \cdot \frac{Pa}{psi}\right]$ Pa; MAWP of the VMTF helium vessel

$T_{inf} = 7$ K; helium temperature

$T_f = \frac{1 \cdot T_{inf} + 1 \cdot T_{coil}}{2}$ K; film temperature

Transport properties

Call **HEPROP** ('', 0, P, T_f : ρ, x) calculate density [kg/m3] at film temperature

Call **HEPROP** ('', 17, ρ, T_f : k) calculate thermal conductivity [W/m-K] at film temperature

Call **HEPROP** ('', 16, ρ, T_f : μ) calculate viscosity [kg/m-s] at film temperature

Call **HEPROP** ('', 6, ρ, T_f : cp) calculate specific heat [J/kg-K] at film temperature

$g = 9.81$ m/s2; gravitational acceleration

$\beta = \frac{1}{T_f}$ expansion coefficient

$\nu = \frac{\mu}{\rho}$ m2/s; kinematic viscosity

$\alpha = \frac{k}{\rho \cdot cp}$ m2/s; thermal diffusivity

Geometry

$D = 0.09$ m; diameter of magnet bore

$H = 4$ m; length of magnet bore

$A_c = \frac{\pi}{4} \cdot D^2$ m2; cross-sectional area of magnet bore

$perim = \pi \cdot D$ m; circumference of magnet bore

$A_s = \pi \cdot D \cdot H$ m2; surface area of magnet bore

$r = 2 \cdot \frac{A_c}{perim}$ m; characteristic radius of magnet bore

Heat transfer

$\Delta T = T_{coil} - T_{inf}$ K; temperaure difference between coil and helium

$q = h_{conv} \cdot A_s \cdot (T_{coil} - T_{inf})$ W; heat transfer rate

$q`` = h_{conv} \cdot (T_{coil} - T_{inf}) \cdot \left[0.0001 \cdot \frac{W/cm2}{W/m2}\right]$ W/cm2; heat flux